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## OPERATING CONDITIONS FOR METAL IN COMBUSTION CHAMBERS OF GAS TURBINES

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Among the requirements for combustion chambers of industrial and transportation gas turbines operating on heavy liquid fuels are mechanical strength and long life. Satisfaction of these two conditions is directly related to the operating conditions for metals in combustion chambers and to their quality.

For a long period, metals in combustion chambers must resist high temperatures and stresses as well as chemical action (oxidation and corrosion).

During the combustion of fuel in the combustion space of the chamber, fairly high temperatures develop, reaching 1,600-1,800°C. Wall temperatures are very high. These depend on such conditions as the temperature of the flame, the initial temperature and pressure of air introduced into the combustion chamber, the presence and method of admitting secondary air through the flame-tube walls into the combustion space, and the cooling-air speed.

The chief factor influencing the temperature of the fuel spray is the initial excess air ratio at which fuel combustion is carried on. A change in this ratio will produce great changes in the temperature. Thus, decreasing the coefficient of excess primary air from 3.0 to 1.5 causes an increase in the average flame temperature from 1,100 to 1,600°C.

The conditions governing the temperature of flame-tube walls become especially difficult when the temperature of the air entering the combustion chamber is very high while the pressure is low. In case heat regeneration is applied in gas turbine motors, the temperature of the incoming air is usually 300-400°. In multistage fuel combustion, this temperature reaches 500-550°C for medium- or low-pressure combustion chambers. At such high temperatures the cooling effect of the air flowing along the flame-tube walls is, of course, very small. The lower the operating pressure in the combustion chamber, the less the heat loss and, consequently, the higher the temperature of the metal parts of the combustion chamber.



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The active cooling medium for tube walls is the introduction of secondary air into the combustion area through these walls. This introduction of air on the inner surface of the flame tube must produce a protective air layer whereby both sides of the flame-tube walls will be cooled. To produce this layer, secondary air must be admitted, not radially, but in an axial direction, so that the air will flow along the inner surfaces of the flame tube in direct contact with these surfaces. This flow of cooling air is obtained by its passage through annular openings between tube sections situated concentrically, one inside the other (see appended Figure 1). The required dimensions of the openings, the length b and, in particular, the height h are determined by the rate of admission of secondary air and the length of the section. Calculations demonstrate that in using this method of introducing cooling air with a temperature of 300°C at the rate of ~40 m/sec, the temperature of the flame-tube walls remains at a level of approximately 800°C when the average flame temperature is ~1,500°C.

The rate of flow of the cooling air flowing along the outer surface of the flame tube exerts a considerable influence on the temperature of the tube walls. Increasing the rate of flow two, three, or four times brings about an increase in the coefficient of heat loss from the flame-tube surface to the air 1.75, 2.4 or 3.0 times, respectively. But the possibilities of wide employment of this method are limited by the simultaneous growth, far greater than that of the heat loss, of the hydraulic resistance together with a pressure drop in the combustion chamber.

The limit for the average temperature of flame-tube metal under ordinary, normal conditions must be considered 800-900°C. One of the plants with experience in gas-turbine building lays down the following condition for metal intended for flame tubes: it should be capable of long operation without oxidation or deformation at a temperature of 1,000°C.

It should be noted that high temperatures in flame-tube walls are not only necessarily obtained by virtue of the operating conditions specified for flame tubes, but that they are likewise necessary for the normal course of combustion processes. Low temperature in the flame-tube walls may cause coking of the drops of atomized fuel falling on the walls. Cold walls can cause fuel vapors coming into contact with them to condense.

Temperatures at different parts of the flame tube are not the same. In general, the maximum metal temperatures occur at that part of the tube where the flame ends and where, consequently, the process of the physical development of the fuel heat attains its maximum. Under ordinary conditions, this will be the last section of the tube. But in certain cases, the metal in the front part of the tube has a higher temperature than that in the back part if, in the back part, a considerable amount of secondary air is admitted into the flame, thus lowering its temperature. In one case, for instance, the temperature of the front part of the tube averaged about 1,000°C, and that of the back, about 700°C.

The mean temperature is not the only determining factor in the life of the metal in a flame tube. Under certain conditions, local heat may greatly exceed the average temperature. The causes of such excessive local temperatures may include asymmetrical distribution of air in the annular space outside the tube, so that part of the tube is not sufficiently cooled, or a bend in the flame, or the flame's striking the tube wall whereby the point of contact would be overheated. With respect to this last-mentioned point, in that part of the tube where combustion is developed and the highest temperatures occur, it is necessary to avoid having projecting parts which could be quickly scorched on contact with the flame.

Local overheating of the metal, causing the appearance of a temperature gradient and nonuniform expansion, is the principal cause of corresponding stresses at this point in the metal and likewise of deformations revealed by bulging (when in sheet form) and cracking. Buckling of the metal may be caused by local scale formation on the tube walls. The scale, acting as a heat-insulating layer because of the poor heat conductivity of carbon, creates a temperature gradient in the metal at the edges of the deposit, resulting in local stresses.

Anotner obstacle to the life of flame-tube metal is the nature of the medium surrounding it, owing to the presence of a large quantity of free oxygen. Even in the gas stream inside the flame tube, as a result of the usual combustion of fuel with considerable air excesses, the oxygen content amounts to 10-15%.

A destructive influence is also exerted on metal by the presence of sulfur dioxide, especially in the large quantities involved in the use of mazuts which industry and transport are seeking to utilize in gas turbines. In fact, in shifting from high-grade types of heavy liquid fuel (diesel, solar oils) to low-grade types (mazuts) the sulfur content of the fuel increases from 0.2 to 1% -- five times -- or, if sulfurous mazuts are used, even up to 4%. For flame tubes in the latter instance, the sulfur dioxide content in combustion products amounts to ~0.08-0.12%, the excess air coefficient being respectively 3-2. Hence it follows that the conditions governing the life of tube metal are also determined by the properties of the fuel used.

The presence of a practically even pressure on both sides of the flame-tube wall, relieving it of mechanical stresses from pressure, is a favorable condition for tube metal. This mechanical relief permits building flame tubes with thin walls, thus improving the air cooling and reducing the thermal stresses in the thickness of the wall -- all the more so because the heat-resistant metals used have low heat conductivity. The usual thickness of flame-tube walls is 3-5 mm. At present, they are generally made of sheet metal. This is due, in part, to limitations on the size and weight of equipment.

Other, less difficult conditions are imposed on metals for the jacket of the combustion chamber. Among these conditions are mechanical loads, since the casing is subject to the internal pressure of the combustion chamber but not to the direct action of the high temperatures of the combustion space. The temperature of the jacket walls is fixed in relation to the temperature of the air passing along its inner surface and the flame-tube surfaces, to the amount of radiated heat its walls receive from the tube, and to the speed of the cooling air passing along the jacket walls.

Table 1 gives examples of the values of the average temperature of the jacket in relation to the initial temperature of the air flowing along it with reference to the same average temperature of 800°C in the flame tube. It follows from this table that, at the given tube temperature, the temperature of the jacket will be quite high even at rather low cooling-air temperatures. The lower the cooling-air temperature, the greater the difference in temperature between the jacket and the air.

Table 1

| Initial Temp of Cooling Air (°C) | Av Temp of Jacket (°C) | Diff in Temp Bet Jacket and Air (°C) |
|---|---|---|
| 200 | 410 | 210 |
| 300 | 445 | 145 |
| 400 | 485 | 85 |
| 500 | 545 | 45 |

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In many cases, to lower the temperature of the metal in the jacket, the jacket is shielded from the air and the flame tube by an insulating layer. To prevent particles of this insulation falling into the cooling air stream and passing with it into the turbine, and to give the proper form to the insulat... layer on the side toward the cooling air, this layer is covered with a thin sheet casing. This type of covering for the insulation is useful in combustion chambers with high pressures (~10 atm and over) and at high initial cooling-air temperatures when the strength of the jacket is especially important.

To decrease the size and weight of combustion chambers, it is possible to use air instead of insulating materials to insulate the jacket. From figures on the heat conductivity of air and insulating materials, it may be assumed that a one-cm air gap between the jacket and the casing is equivalent to a thickness of about 5 cm in the insulation generally used for combustion chambers.

To lower the temperature of the casing walls, it is advisable, especially with low initial cooling-air temperatures, to use a screen of thin sheet steel installed in the gap between the flame tube and the jacket. As shown by calculations, the jacket temperature can then be reduced to a value exceeding the temperature of the cooling air by no more than 20-30° C.

Data on the operation of one combustion chamber on mazut may be cited as a concrete example. The cooling air entered the combustion chamber at an initial temperature of 150°C and a pressure of ~3kg/sq cm. When there was no screen in the combustion chamber, the flame-tube temperature averaged ~1,080°C, the jacket temperature 500°C. With a screen, the flame-tube temperature remained about the same (~1,050°C) but the temperature of the jacket was reduced to 200°C, moreover the temperature of the screen itself was 500°C.

Hence, for metal in a jacket it is possible to establish minimum temperatures under combustion-chamber conditions which either somewhat exceed the temperature of the cooling air, or may be even lower if internal insulation is used.

To prevent the occurrence of mechanical stresses in the metal from heat expansion, combustion chambers must be so constructed that their individual parts are free to expand. For this reason, the back of the flame tube is usually not fastened, so that, when it expands, this end of the flame tube can slide along the casing. The front of the flame tube, where the device for admitting the primary air is located, is securely fastened. If necessary, additional braces are put in to prevent buckling and sagging in the tube. These braces must be movable to permit play for both axial and radial expansion in the tube. Sometimes the surface of the thin-walled parts of the combustion chamber are semicorrugated to increase rigidity. Corrugated expansion pieces are usually installed on the jacket to compensate for its expansion. Allowance for heat expansion is especially necessary in combustion chambers because the heat-resistant metals used in them have different coefficients of linear expansion.

Welding is extensively used in standard construction of flame tubes and combustion chambers. Consequently, metals for them must be capable of being well welded, but the combustion structure should have as few welds as possible. A welded seam in heat-resistant metals is weaker both as to resistance to wear and as to corrosion than an unwelded part. However, metallographic research on welded joints and X-ray inspections have contributed greatly to the successful utilization of welding in building combustion chambers.

The general complications of air-supplying and air-mixing devices in a flame tube make one more technological requirement (besides weldability) essential for metals. They must be pliable and easy to stamp or bend.

In initial experiences with turbojet engines, cracks were observed in the jackets of multitube combustion chambers after a short period of operation. They occurred for the most part near welds, less often at a distance from welds in intact parts of the metals. They were fatigue breakdowns. Study of these breakdowns showed that their cause was not the welding but fine vibrations developing in the jacket when the air from the compressor entered it. Oscillograph studies of the pressure of the air on entering the chamber indicated the presence here of appreciable variations in pressure covering a wide frequency range of about 60 kilocycles. In individual cases, pressure oscillations amounted to 70% of the average pressure in the jacket. Since it was difficult to imagine that pressure oscillations themselves could cause damage, it could only be assumed that any of the existing frequencies would prove capable of amplifying resonance vibrations and causing corresponding stresses which then became the direct cause of rapid fatigue breakdowns. Attempts to lengthen the life of a casing by using thicker austenitic steel and shifting to autogenous or arc welding produced no positive results. Service life was successfully lengthened (to 100 hr) after replacing austenitic steel with soft carbon steel. Hence we may conclude that, apparently, soft steel possesses much greater shock-absorption power than austenitic steel and that this absorption will fully compensate for its lower yield point and resistance to cracking (Physics and Chemistry of Reactive Motion, Sbornik 3, 1949).

Later, welded multitube combustion chambers for turbojet engines were replaced by chambers made of drawn-soft steel with a nickel coating on each side.

The above-mentioned problems relating to the chemical stability and mechanical strength of metals in combustion chambers for industrial and transport gas turbines cannot be regarded as isolated questions. They must of necessity be linked with the requisite lifetime of such turbines. Such a combination of operating conditions may explain the use of thicker flame-tube walls in combustion chambers intended for turbines as compared with combustion chambers for turbojet engines.

In general, the total life of a combustion chamber should correspond with the assigned life of all the mechanisms of a gas turbine which, whether for stationary or transport purposes, is intended to operate for 100,000 hr. It is obvious that such long operation cannot be expected of flame tubes and mixing devices since they are made to operate under very difficult temperature conditions. No practical experiments have been conducted on the possible length of service of the flame tubes and mixing devices. In any case, the following relationship must be stated: the longer the life desired for flame tubes and mixers, the lower their operating temperatures must be. Low temperatures are guaranteed by proper construction of the combustion chamber.

From the foregoing analysis of the conditions governing the life of combustion chambers, it is evident that, if the metal for the jacket must, first of all, possess fairly high qualities of mechanical strength, the metal for the flame tube must have the greatest possible resistance to the chemical action of air and gas media as well as high temperatures. The chief evidence of this resistance is slowness in forming scale.

The varied conditions for the life of tubes and jackets require that the metals used to build them also differ in quality and type. Heat-resistant, high-alloy metals with a high degree of resistance to corrosion by gas are used in constructing flame tubes. By resistance is meant the ability of a metal, at high temperatures, to withstand the oxidizing effect of the gaseous medium (oxygen, sulfur dioxide) surrounding it. The result of this action on the surface of a metal is the formation of scale which gradually makes the metal thinner. The criterion for this basic property of metal for tubes is loss of weight during oxidation. To ensure long service, losses in weight must be as small as possible. The total loss over a given time predetermines the thickness required for the wall of a flame tube.

The most widely used metal for tubes is chrome-nickel steel containing ~25% chrome and 20% nickel. For this 25-20 steel, reliable, continuous operation may be considered possible at temperatures as high as ~800-900°C. For tubes in turbojet engine operation, it is preferable to use alloys with a nonferrous base, particularly chrome-nickel alloys in which nickel, the basic component, amounts to approximately 75%. It is, however, a well-known fact that metals with a high nickel content are particularly sensitive to sulfurous gases, which promote the formation of a fusible, sulfide eutectic, contact with which greatly reduces the heat resistance of the metal.

Hence, in cases of higher sulfur content in combustion products and high temperatures in tube walls, it may be impossible to employ high-nickel alloys despite the great value of nickel as a heat-resistant metal. The maximum sulfur dioxide content is considered 2 g/cu m.

The choice of metals for jackets is comparatively simple. When, by some means or other, comparatively moderate temperatures can be obtained for jacket walls, it becomes possible to use mild carbon steel. At higher temperatures, heat-resistant steels are used, such as low-alloy, chrome-molybdenum steel (Ni, 2%; Cr, 0.35-0.6%; Mo, 0.35-0.6%) or 18-8 steel (Cr, 18%; Ni, 8%).

A more effective method of lengthening the life of combustion chambers might be to (1) line the tubes with refractory materials, (2) protect them with a ceramic coating, or (3) replace metal tubes with ceramic ones. Such materials would permit raising the temperature in the tube walls, which would aid combustion processes, and would not require the great velocity of cooling air needed to ensure elimination of heat from the tube walls. For this purpose, it would be necessary to have refractories or ceramics capable of excluding the possibility of independent cracking and crumbling and obviating the danger of particles falling from them into the gaps between the rotating and immovable parts of the turbine. However, the defects of known refractories are their brittleness under concentrated stresses and their low resistance to thermal shock, which are especially strong at the starting and stopping of combustion chambers.

An inevitable future rise in the operating temperatures of gas turbines and the increasingly difficult conditions governing the life of metals are reasons for intensifying work on finding and using durable refractories and ceramics to replace metals at the necessary points in combustion chambers.

[Figure follows.]

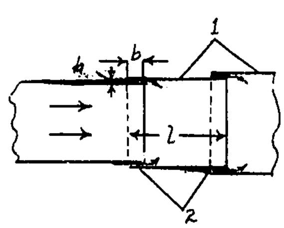


Figure 1

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